APPLICATIONS OF ULTRASONICS IN GEOLOGY

Senior Thesis

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by

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SECTION I

INTRODUCTION

A method which is somewhat similar to sonar is used to measure the thickness of a test site. An ultrasonic (200KHz) signal is propagated through the test site until it reaches a distinct interface, such as an abrupt change in density due to a change in the material the signal is being propagated through, which causes it to be reflected back to its source. This reflected signal is then displayed on an oscilloscope. By using an oscilloscope with a dual time base, it is possible to measure within one per cent the time it takes this signal to make its journey. The velocity of the signal through this test site is then measured. The thickness of the test area can be determined by using the following formula: Thickness = velocity times transit time. The overall accuracy of the gage as observed in the laboratory was better than two per cent.

Three basic problems were encountered in the development and use of the gage: (1) Since the velocity of an ultrasonic signal through any medium is directly related to the density of that medium, to accurately measure test sites of different densities, it is necessary to accurately determine the velocity of the ultrasonic signal at each test site. (2) In a heterogeneous material the variations in particle size and density cause a scattering and partial reflection of the ultrasonic energy. (3) The amount of energy coupled into the test site is proportional to the area of the test site that is parallel to and in contact with the base of the transmitter. A rough top surface tends to cause a reflection of the sonic energy before it is coupled into the test site.

In addition, a rough bottom surface tends to cause reflection of the sonic energy at random angles. Thus, some of the sonic energy will be reflected back from the bottom surface at such an angle that it will not be picked up by the receiver which is placed in the center of the transmitter. Heterogeneous material and surface roughness can cause a severe attenuation in reflected signal strength and quality (Fig. 1).

THE SYSTEM DEVELOPED

The device used to introduce the ultrasonic energy into the test site (Fig. 2) has an 18-inch outside diameter, a 6-inch inside diameter, and weighs approximately 55 lbs. An exploded view of the transmitter is shown in Figure 3. The wedge-shaped units are the heart of the transmitter. These units, which are polarized ferroelectric-ceramics, respond to electrical stimulation in a manner

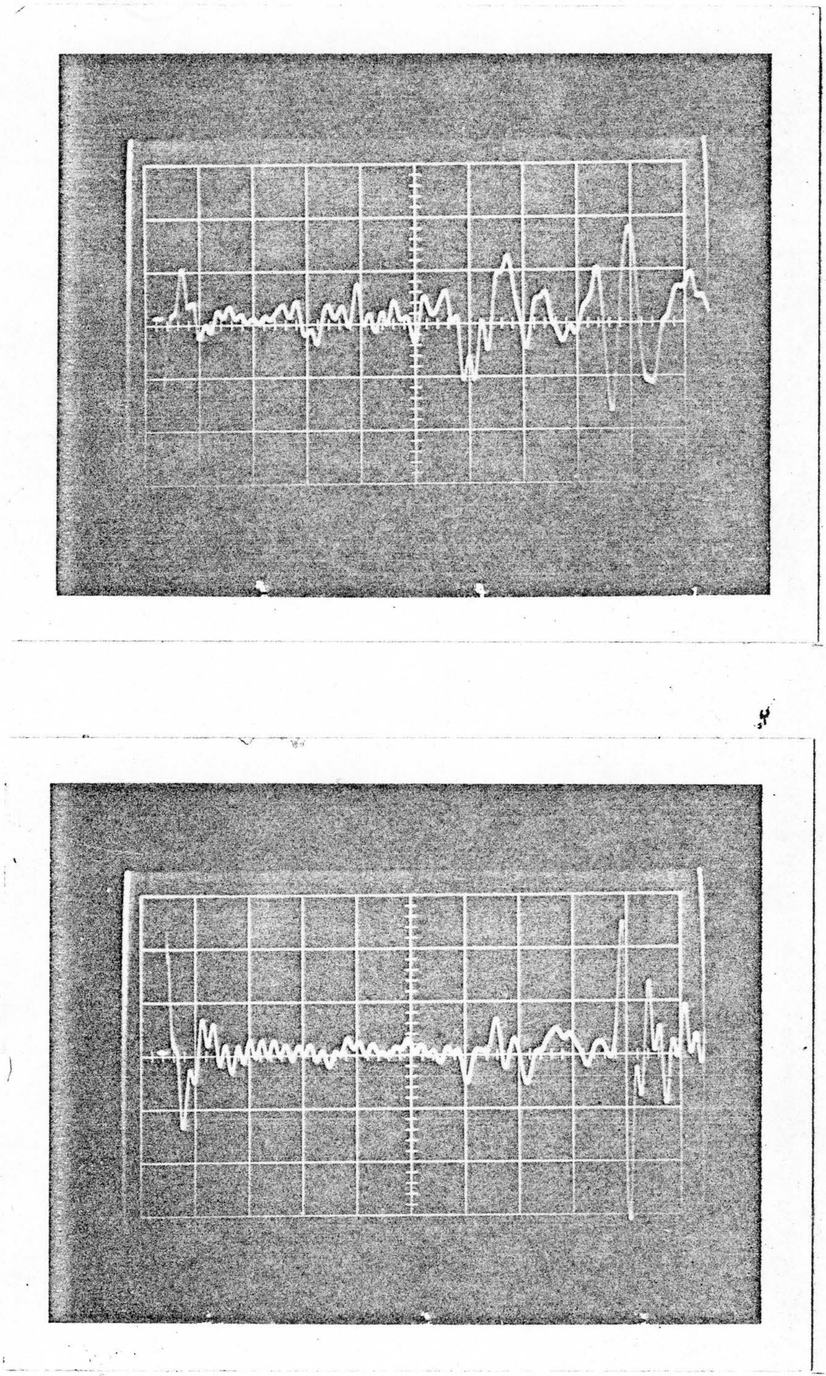


Fig. 1 Comparison of reflected ultrasonic signals through concrete (heterogeneous) and limestone (homogeneous).

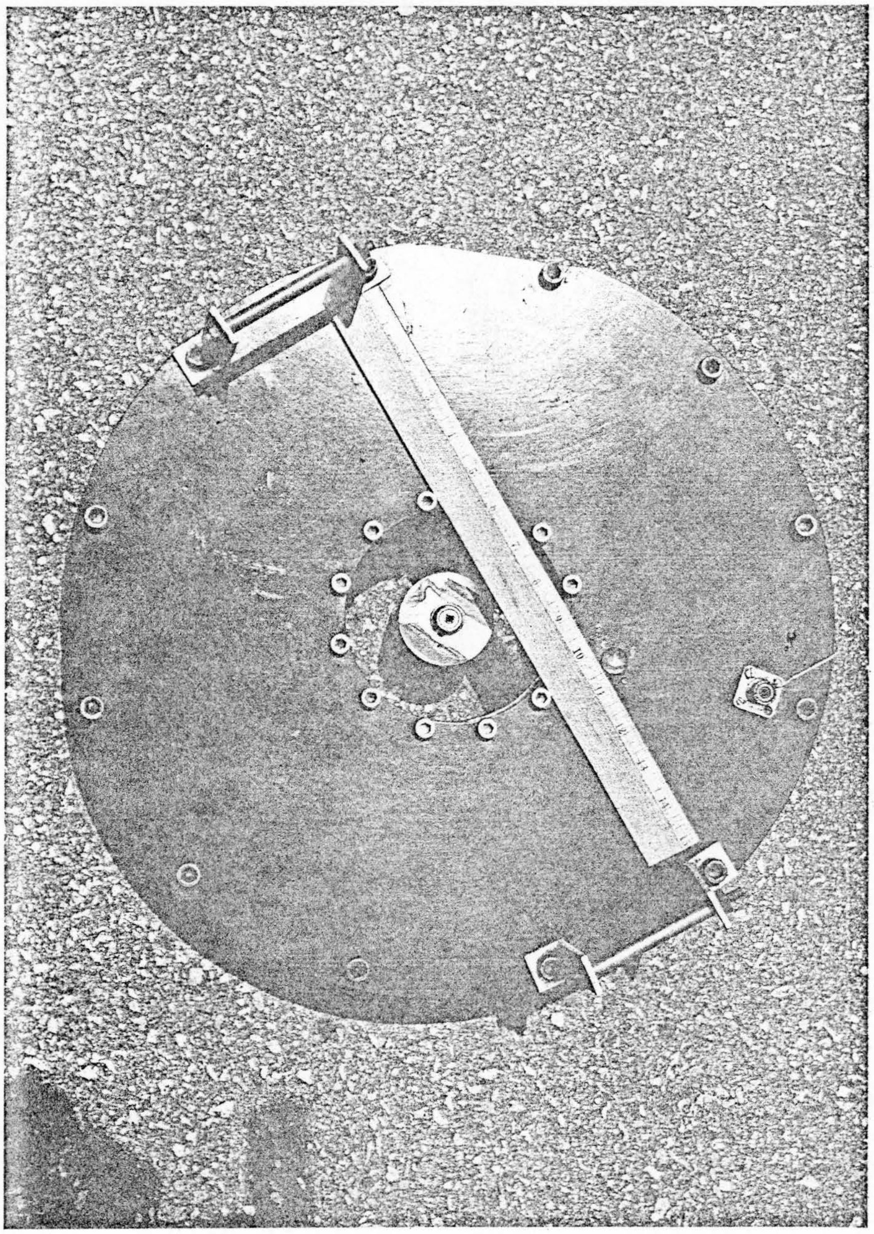
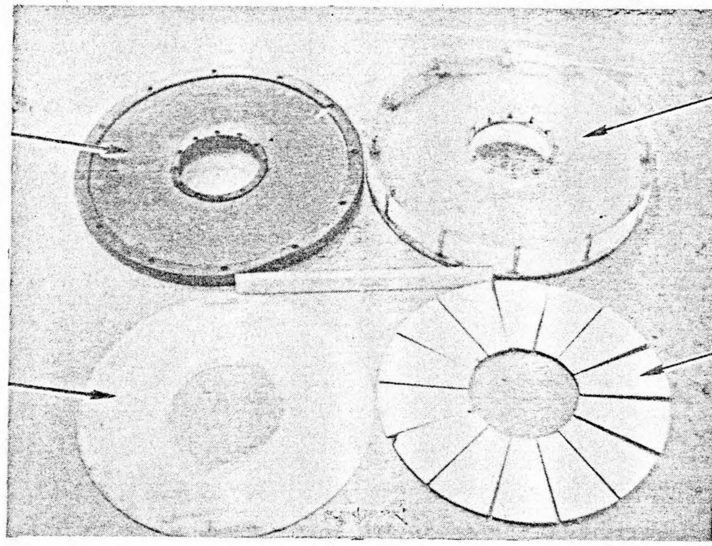
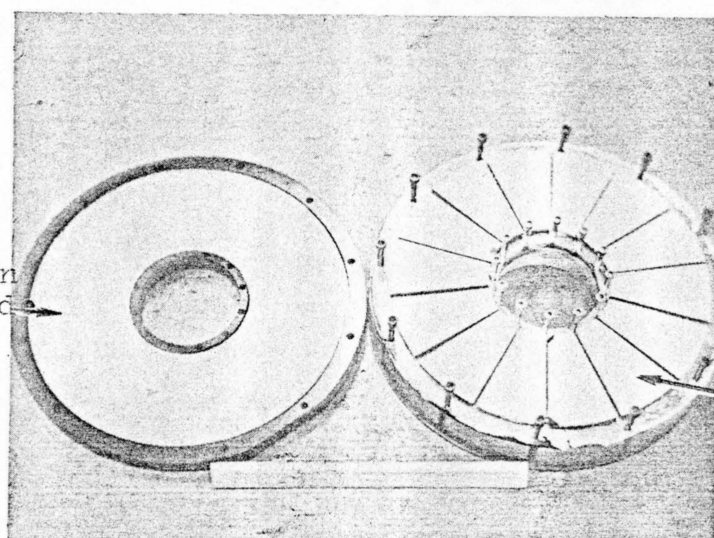


Fig. 2 18-inch diameter acoustic transmitter fully assembled. The small transducer in the center is the receiver.



(a)



(b)

Fig. 3 Dissembled view of the 18-inch diameter transmitter.

similar to that of piezoelectric crystals. They convert electrical energy into acoustic (mechanical) energy by vibrating when an alternating electrical field is applied across them. Electrical contact is made between the ceramic wedges and the positive output of the pulse generator via a copper plate placed between the top of the transmitter and the ceramic wedges. The negative side of the pulse generator is electrically connected to the transmitter through a thin layer of conductive paint which is applied to the top surface of the plastic base plate. The ultrasonic signal travels from the ceramics, through the plastic base plate (Fig. 3(a)), through a liquid (glycerine) couplant, and into the test site. The liquid couplant must be used because the ultrasonic wave will not propagate through the air interface between the transmitter base and the surface of the test site.

After being coupled into the test site, the ultrasonic signal travels through the test material until it comes to a discrete interface. It is then reflected back through the material where, at the surface at which the signal was coupled into the test site, it is received by a 2.25-inch diameter, high frequency (5MHz), lithium sulfate, mechanical-to-electrical transducer which is located in the center hole of the transmitter. This transducer converts the reflected acoustic wave into an electrical voltage. This voltage is displayed on the screen of an oscilloscope and from its position on the screen, the transit time of the signal can be determined.

The ultrasonic velocity is measured using two James Transducers (Fig. 4). These transducers utilize rochelle salt crystals which are cut to operate at a frequency of 20KHz. The crystals are immersed in an oil bath under pressure. The ultrasonic velocity is found as follows:
(1) The transducers are placed a fixed distance apart and one of them is electrically excited. The ultrasonic wave generated by this transducer will radiate out in all directions and thus be picked up by the other transducer.
(2) The signal received by this transducer is displayed on an oscilloscope. From the position of the signal on the oscilloscope, it is possible to determine the time it takes the signal to travel from one transducer to the other.
(3) The ultrasonic velocity is calculated by dividing the transducer separation distance by the transit time of the signal. The accuracy of the velocity measurement is nominally ± 1 per cent.

The electrical system used in the ultrasonic gage is representative of a typical A-scan configuration often

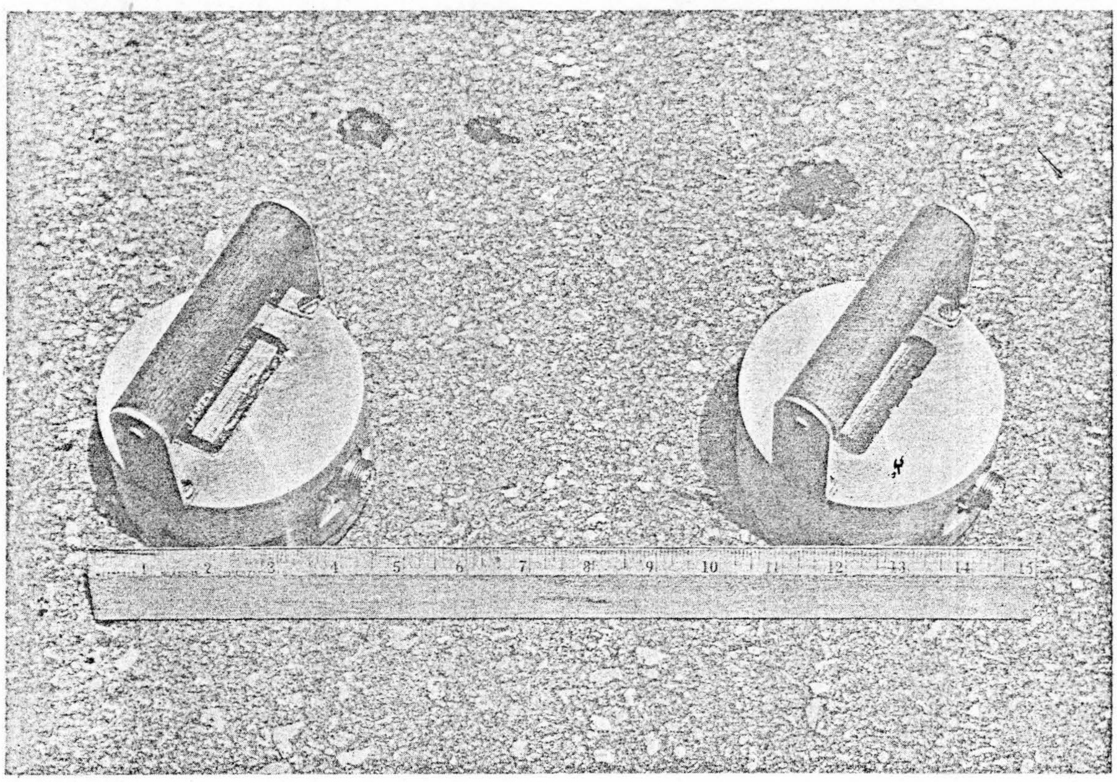


Fig. 4 The 20kHz James Transducers used to measure the ultrasonic velocity.

found in ultrasonic nondestructive testing. This type of presentation displays ultrasonic signal amplitude (vertical axis) as a function of time (horizontal axis). The unit that provides the timing and the pulse excitation for the ultrasonic system is a typical multivibrator-thyratron configuration. The pulse unit is capable of delivering 1200 volts at 75 amperes to a 5 ohm capacitive load in 2 microsecond pulses.

SYSTEM PERFORMANCE

The system has an overall accuracy of $\pm$ 2 per cent in the laboratory for a range of thicknesses of 4 to 12 inches. The materials tested in the laboratory were Indiana limestone, mortar, and concrete. As expected, the results on the limestone were more accurate than those on the concrete. The concrete is very heterogeneous material (equivalent to a well-cemented conglomerate) and attenuated the ultrasonic signal much more than the limestone or the mortar did. The large pebbles in the concrete led to a random scattering and reflection of much of the ultrasonic signal. This resulted in a small signal-to-noise ratio and a distorted signal presentation on the screen of the oscilloscope. Thus, it would seem reasonable to say that the more homogeneous a material is the more accurately it can be measured. Also, since the signal attenuation in homogeneous material is not as severe as in heterogeneous material, a greater homogeneous thickness can be measured with the same amount of energy.

SECTION II

RESULTS OF FUNDAMENTAL STUDIES

DESCRIPTION OF SOUND-FIELD PATTERNS

The transit-time measurements of the gage are based on fundamental concepts of sound divergence from an acoustic radiator. As a pulse of ultrasonic energy propagates down through the material being tested, the sound spreads out. Figures 5 and 6 show the approximate profile of the sonic beam developed by the 18-inch plastic-based transmitter.

For a circular radiating disc, the angle of spreading is given (Wood, 1957, p. 157) as:

$$\sin \theta = 1.22D \tag{1}$$

Where: θ (degrees) = Angle of divergence measured with respect to the axis of symmetry of the disc and located beyond the Fresnel or Near Field Zone

λ (inches) = Wavelength of sound in the propagation medium

D (inches) = Diameter of the transmitting disc

This equation is valid for (1) a continuously vibrating disc, (2) radiating into an infinitely large medium with no reflecting surfaces, (3) with a uniform pressure amplitude across the face of the disc, and (4) provided the plane around the disc is infinitely stiff (clamped). Clearly

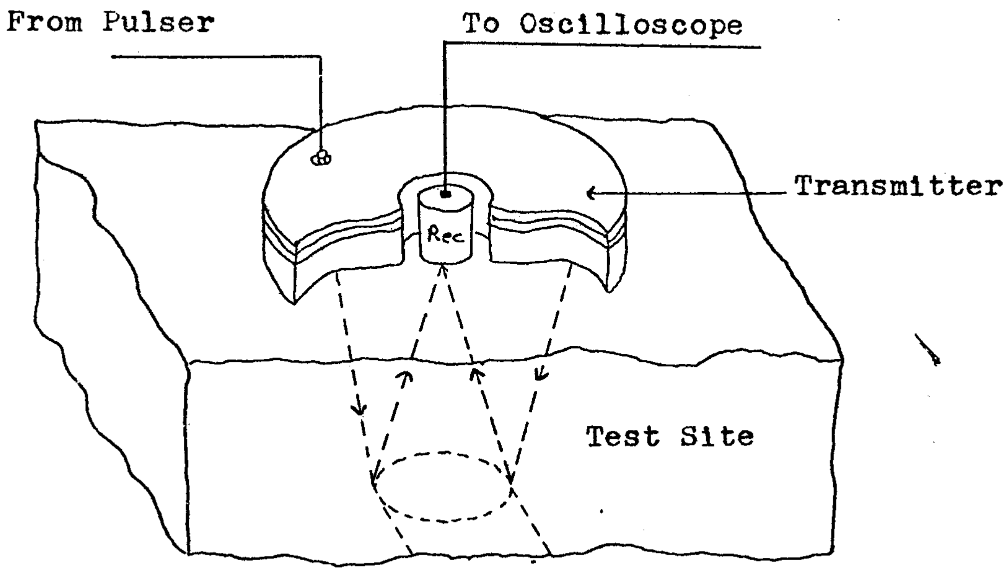


Fig. 5 Functional drawing of the ultrasonic transmitter and simplified sonic beam profile.

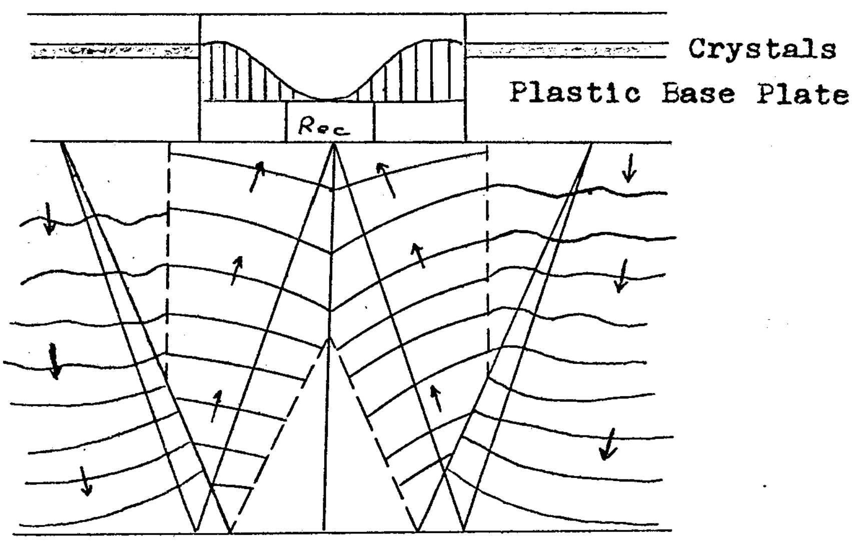


Fig. 6 Schematic drawning of the sound fields in the vicinity of the ultrasonic transmitter.

this equation is only an approximation to the field normally generated by ultrasonic transducers. However, it serves well as a first approximation to the solution of the beam profile problem. This beam spreading effect makes it possible for a sound pulse reflected from an interface to be received by a receiver placed inside of a large ring transmitter.

CURVED RADIATOR CONCEPT OF ACOUSTIC FOCUSING

Originally, the desire for large amounts of ultrasonic energy gave rise to the curved radiator concept. It was thought that this arrangement (Fig. 7) could could focus the sonic beam in such a manner that the reflected ultrasonic energy would be concentrated in the region of the centrally-located receiver transducer. The transmitting piezoelectric crystals were mounted on the back of an aluminum structure which was to serve as the lens for focusing the sonic beam. An elliptical surface of revolution was used to minimize the effects of spherical aberration. The coupling material between the lens and the test site was chosen to be a mixture of sand and cement mortar, so that no appreciable distortion of the focal zone would be introduced. No significant bending of the ultrasonic beam at the mortar-test site interface was expected.

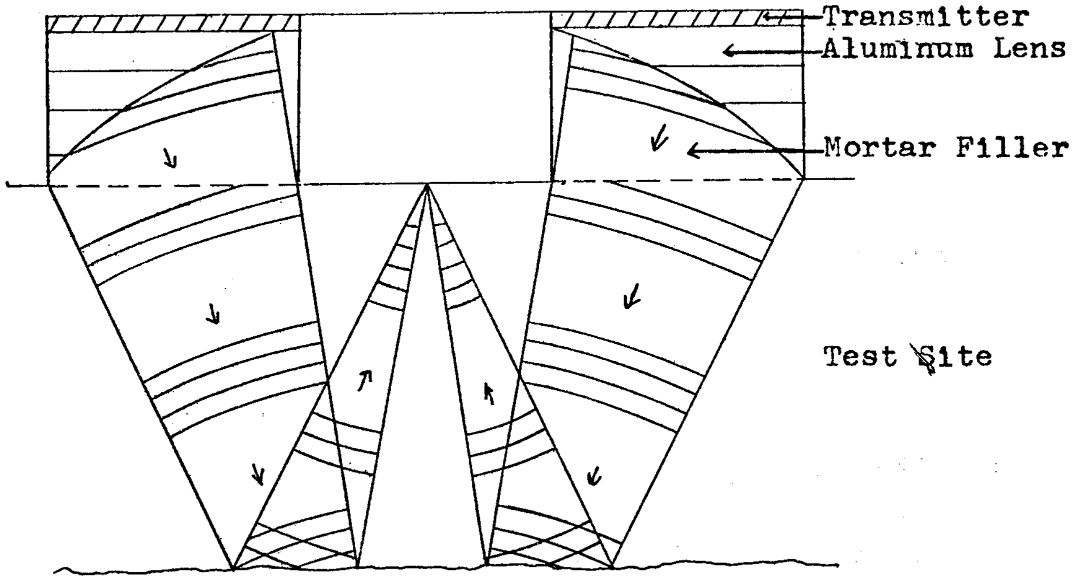


Fig. 7 Schematic drawing of the sound fields in the vicinity of the curved radiator.

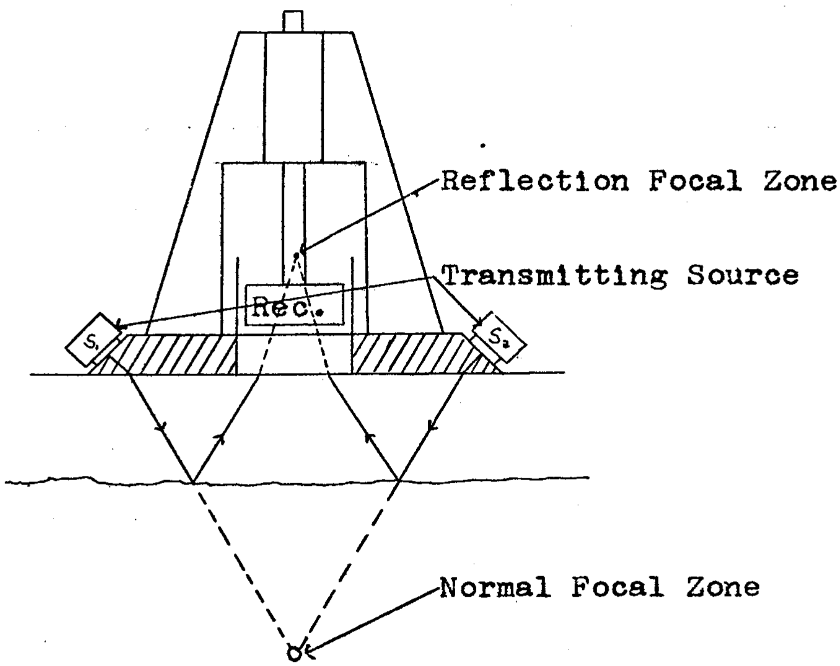


Fig. 8 Sound pattern expected with prototype lens.

The ultrasonic lens itself used a large number of moderately sized crystals (2.5 inch diameter) which acted together to simulate a continuous lens. Figure 8 shows two of the crystals acting as radiating sources at positions S_1 and S_2. The sonic energy first entered the lens structure after all crystals had been excited simultaneously. The sonic signal then arrived at the receiver crystal face R. The focal zone was found by vertical movement of the receiver through the water bath until the peak voltage was obtained. Through calibration techniques on test blocks, it was thought that the test site thickness could be measured accurately.

The curved lens system was tested and found to emit low acoustic energy for the range of electrical energy being put into the system. The low output was traced to two significant factors:

(1) The mortar filler greatly attenuated the high frequency ultrasonic waves.

(2) The aluminum-mortar interface reflected the ultrasonic energy to a large degree.

Thus, the major problem was the lens-mortar interface. Various methods of coupling were tried in order to alleviate this problem, including:

(1) Soft-metal surface conforming techniques

(2) Assortment of oil and grease couplants

(3) Pressurized oil

The pressurized oil method was the best, but still only a weak signal (10-20 mv) was reflected through a 9-inch mortar test block. The curved lens system was abandoned following investigations with a flat, large area radiator. The signals received through the 9-inch mortar test block with this unit were much larger (200-300 mv) than those obtained using focusing techniques.

FLAT RADIATOR CONCEPT

The advantages of the flat radiator were initially discovered when a flat radiator was built for comparison with the curved radiator. The first flat radiator transducer constructed used a 3-inch thick aluminum base plate with clamped piezoelectric ceramic elements (modified Barium Titanate). The transmitter had a 6-inch I.D. hole and an 18-inch O.D. All experiments indicated that the ultrasonic energy output was larger for the flat radiator than for the curved radiator.

Experiments were performed on the flat radiator to determine the profile of the sound field being reflected to the receiver. The expected sound field is shown in Figure 9. The measured results agreed in general with the predicted results. The central lobe, or large peak around

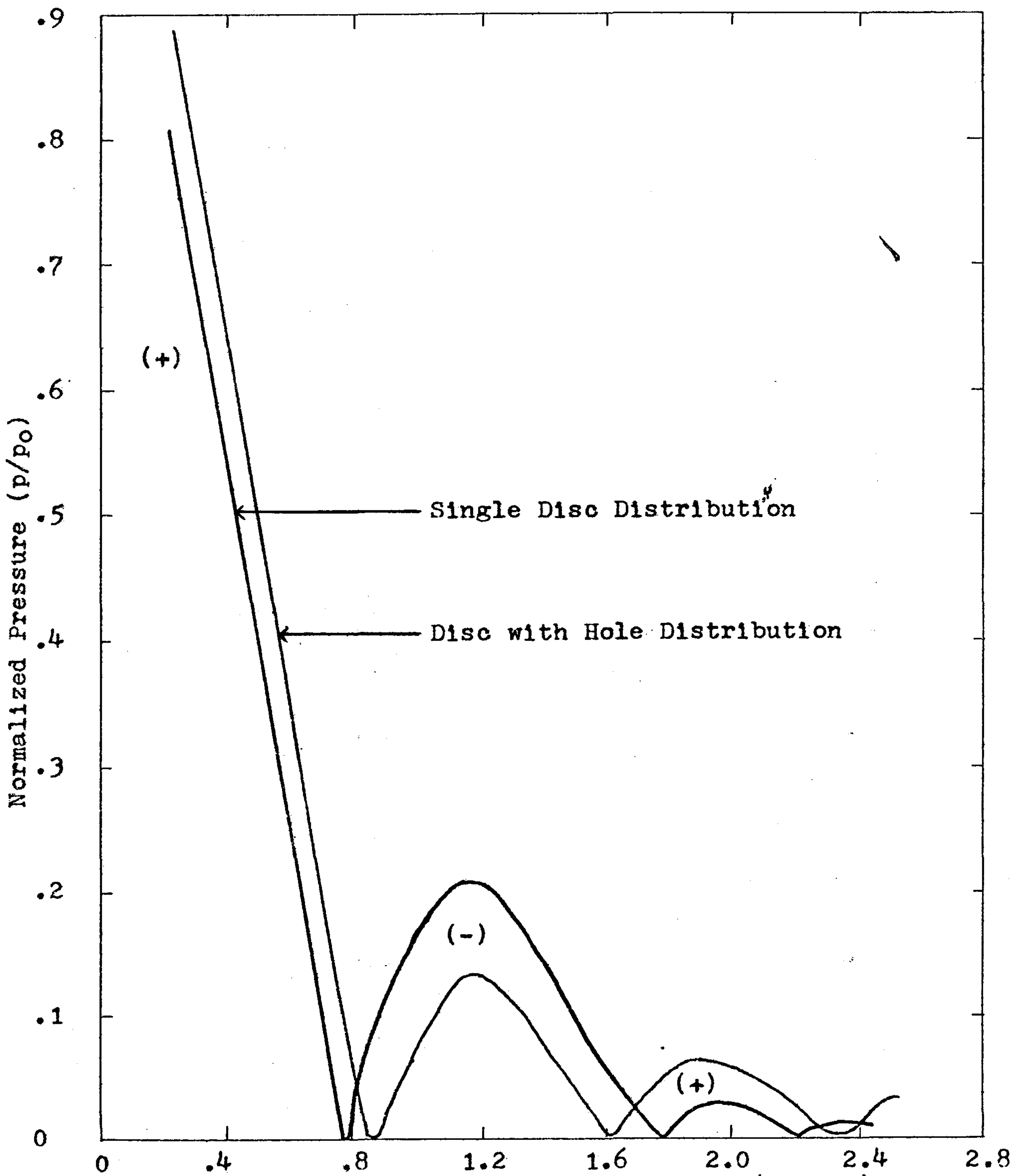


Fig. 9 Profile of reflected acoustic intensity in the region of the receiver plotted as a function of distance from axis of symmetry of transmitter.

zero, extends from the center of the 6-inch hole to about 0.75-inch radially from the symmetry axis. This agrees closely with Eq. (1) which predicts the same result from the beam divergence effect alone. The other secondary lobes or peaks arise from the wave nature of sound. A 2.25-inch diameter receiver will collect all of the ultrasonic energy from the central lobe and also some energy from the secondary lobes.

IMPEDANCE EFFECTS AT INTERFACES

When ultrasonic waves pass from one medium into a second medium at normal incidence (perpendicular to the interface), some ultrasonic energy is transmitted across the interface into the second medium, and some of the energy is reflected back into the first medium. The relative amounts of transmitted and reflected energy depend upon the acoustic-impedance characteristics of the two materials involved at the interface. The acoustic-impedances of materials are functions of their densities and sound velocities.

Thus:

$$Z = vp \qquad (2)$$

where:

Z = Acoustic impedance (grams/cm-sec^2).

p = Density of material (grams/cm^3).

v = Velocity of sound in the material (cm/sec).

The impedance ratio is defined as:

$$r = \frac{Z_2}{Z_1} = \frac{v_2 p_2}{v_1 p_1} \tag{3}$$

The subscripts $_1$ and $_2$ denote the first and second materials respectively. The ratio between the incident acoustic power, W_i, and the transmitted power, W_t, is given by the transmission coefficient T (Goldman, 1962, p. 74):

$$T = \frac{W_t}{W_i} = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} = \frac{4r}{(r + 1)^2} \tag{4}$$

The portion of the incident power, W_i, reflected back into the first (or coulping) medium is given by the reflection coefficient, R:

$$R = \frac{W_r}{W_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = \left(\frac{r - 1}{r + 1}\right)^2 \tag{5}$$

Figure 10 is a graphic solution to Eq. (4). For example, an impedance ratio of 10:1 yields a transmitted power of only 33 per cent of the incident acoustic power. The graph shows that the lower the impedance ratio, the greater the amount of energy which will be transmitted across the interface. Thus, in order to obtain maximum energy transfer across any interface between two dissimilar materials, it is necessary to match impedences as closely as possible.

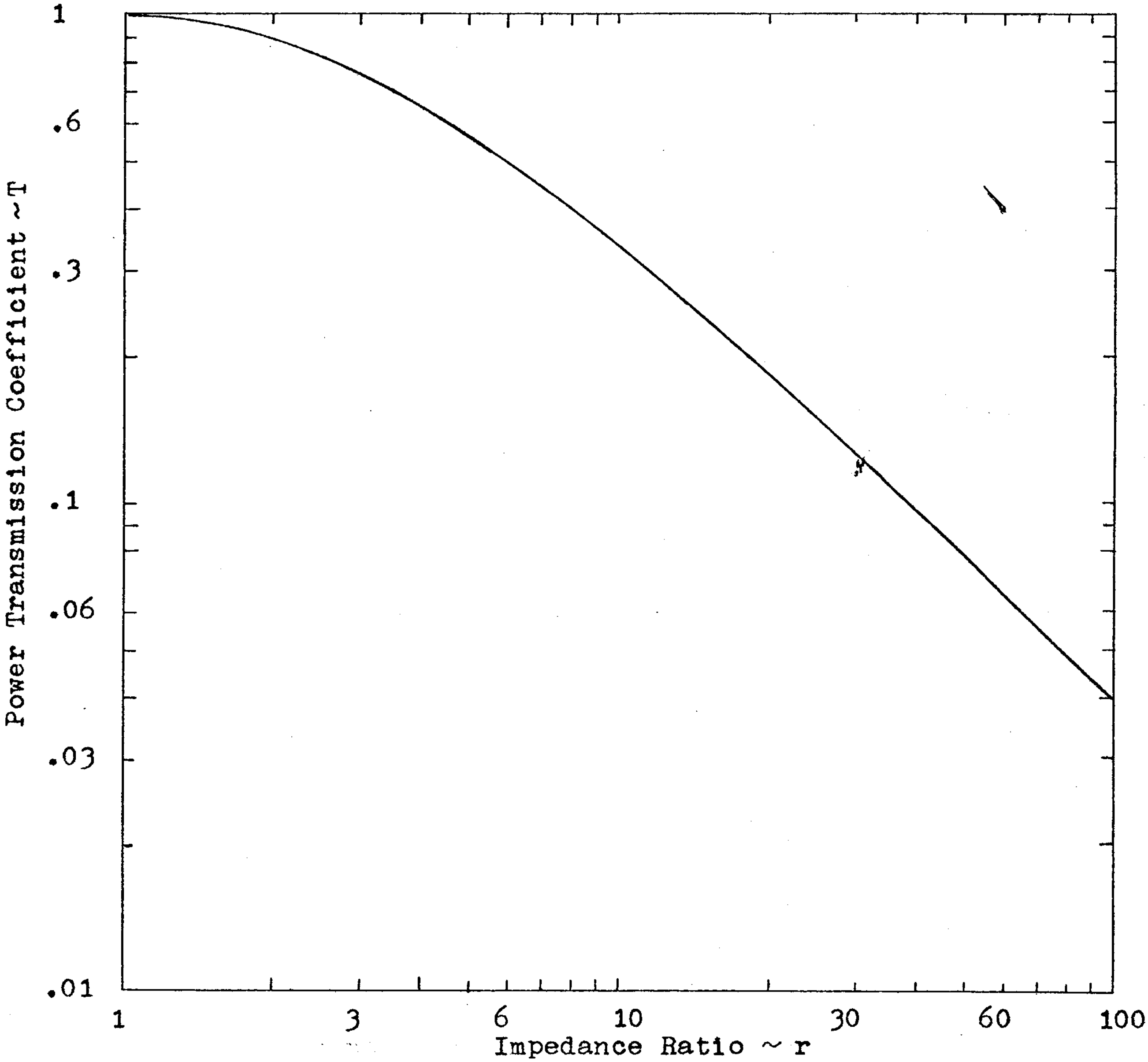


Fig. 10 Power transmission coefficient as a function of impedance ratio.

In the case of material such as limestone, mortar, or concrete, the sound velocity, v, and the density, p, can vary considerably. As shown in Figure 11, longitudinal wave velocities increase with increasing density in concrete. In a series of concrete test cores, density varied from 1.93 to 2.27 grams/cm^3. The sound velocities varied from 11,000 to 13,500 feet/sec as the densities increased. The corresponding acoustic impedances varied from about 6.5 to about 9.5 grams/cm-sec^2 (Fig. 12). The acoustic impedances were calculated from the data of Figure 11 by means of Eq. (2).

The transmission ratios (from Eq. (4)) with glycerine as the couplant show a variation from 70 per cent for lower densities to 65 per cent for higher densities (Fig. 13). Figure 14 shows the net transmission losses of two passages across the interface. The transmission ratios are obtained by squaring the transmission ratio for one passage across an interface. Transmission ratios for various materials are shown as a function of concrete density. Glycerine is used as a couplant because it gives large transmission ratios, it is easily obtainable, and it has a high viscosity which allows it to remain as a cohesive film between the transmitter and the test site.

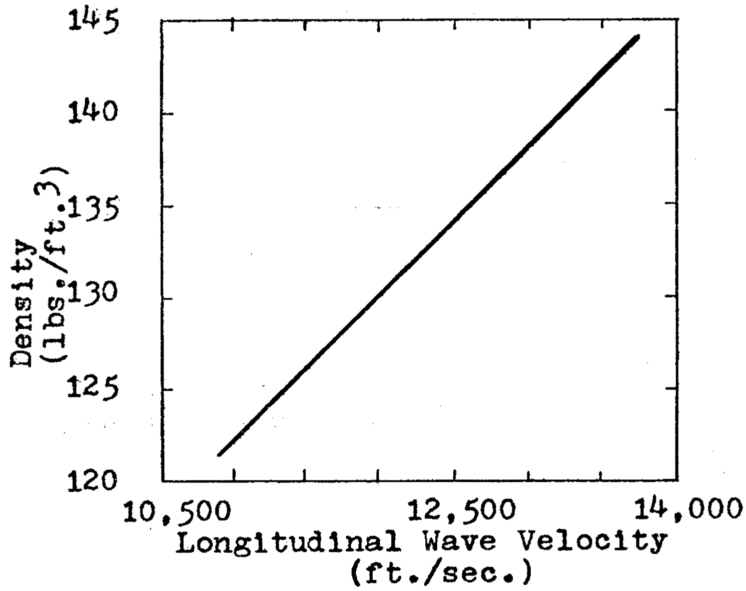


Fig. 11 Relationship between density and longitudinal wave velocity in concrete.

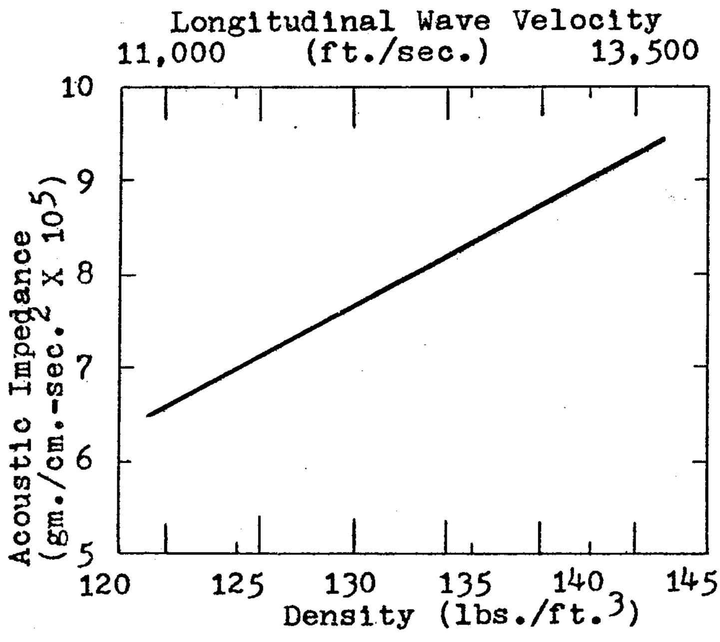


Fig. 12 Relationship between longitudinal velocity, density, and specific acoustic impedance in concrete.

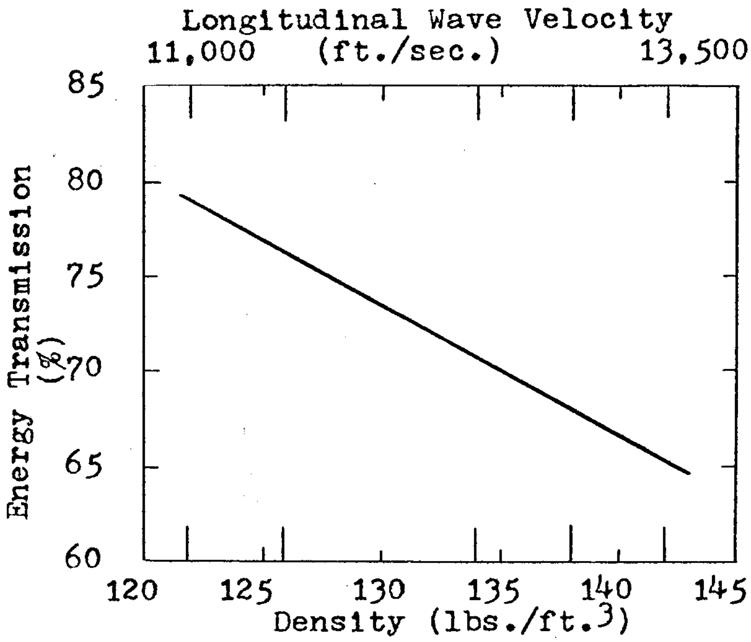


Fig. 13 The relationship between density, sound velocity, and per cent power transmitted into concrete with glycerine as the couplant.

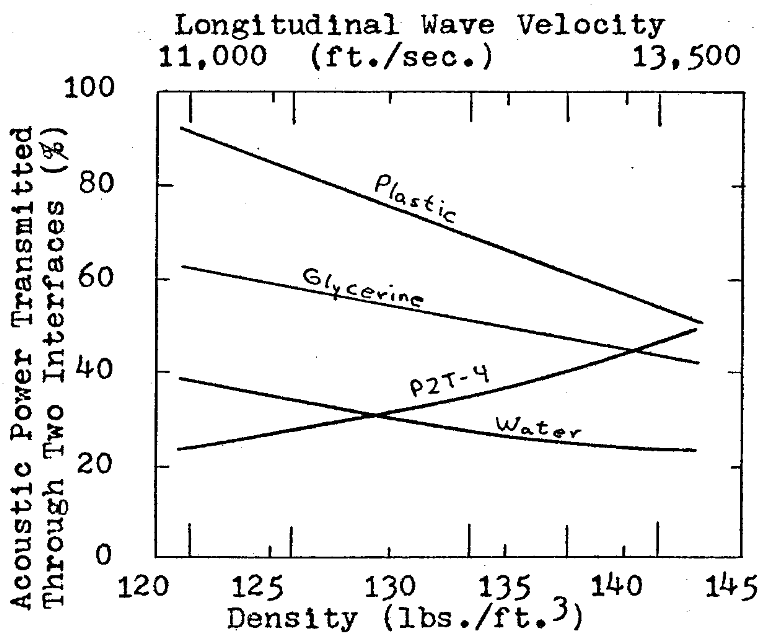


Fig. 14 The relationship between density, sound velocity, and per cent power transmitted through two interfaces of concrete and plastic, concrete and glycerine, concrete and PZT-4, and concrete and water.

ATTENUATION EFFECTS IN HETEROGENEOUS MATERIALS

As an ultrasonic beam passes through a material, energy is lost because of (1) intrinsic attenuation in the material, (2) losses in the coupling medium connecting the transmitter to the material, (3) reflection and refraction of sound energy from internal boundaries in the material, and, (4) losses due to scattering by the rough surface of the material.

Ultrasonic waves are intrinsically attenuated by the material being tested. The beam is weakened by energy absorption and scattering as it propagates through the test material. For plane wave propagation, the sound energy falls off exponentially as (McMaster, 1959, p. 43):

$$I_x = I_o e^{-2dx} \qquad (6)$$

where:

I_o = Initial sound intensity (watt-sec).

I_x = Intensity at point x (watt-sec).

x = Distance from zero reference (cm).

d = Attenuation constant (nepers/cm).

The piezoelectric elements are separated from the surface of the test site by the plastic base plate. There is a loss of energy at the plastic-test site interface. This loss arises because the impedance of the plastic base is not equal to the impedence of the test site. This impedance mismatch produces some sound reflections back into the plastic. The sonic beam is then further attenuated as it propagates through the material because of scattering and absorption. The remaining signal will be partially reflected at the bottom surface.

The amount of reflection is dependent upon the bottom surface conditions. Essentially 100 per cent of the remaining signal will be reflected if it encounters a discrete, smooth interface with the plane of the interface perpendicular to the line of propagation of the signal. However, even in the laboratory, these conditions are seldom if ever met. In reality only a small percentage of the signal is reflected in such a manner as to remain useful.

When sonic waves travel from one medium to another, interface irregularities or critical surface roughness can contribute to loss of sonic intensity and to scattering. There are certain degrees of surface roughness that can produce phase cancellation in the transmitted wave, even with normal incidence. The ultrasonic signal may be penetrating the test site in some areas while still traveling through the couplant in other areas (Fig. 15).

The signal that travels through the liquid has a lower velocity than the signal penetrating the solid. A condensation wave combines with a rarefaction wave when the difference in travel time through this intermediate layer is equal to one-half the period of the sound wave.

Consequently, the sound beam energy is nearly zero within the solid material. The average peak-to-valley roughness that causes this destructive interference is known as the critical roughness, and is given by:

$$R_c = (\lambda_2 v_1)/2(v_2-v_1) = (\lambda_1 v_2)/2(v_2-v_1) \quad (7)$$

where: λ = wavelength of sound in the couplant and test material respectively (inches).

v_1, v_2 = velocity of sound in the couplant and test material respectively (in/sec).

Similar effects occur at multiples of the critical surface roughness, $2R_c$, $3R_c$, etc. The critical surface roughness varies with the test frequency, f, or sound wavelengths, λ_1 and λ_2, which depends upon the sound velocities in the liquid and solid materials.

Another factor which can decrease the sonic energy available for testing is the test frequency employed. The rate at which an ultrasonic signal is attenuated is dependent upon the frequency and the wavelength of the signal used. Lower frequencies are less attenuated in

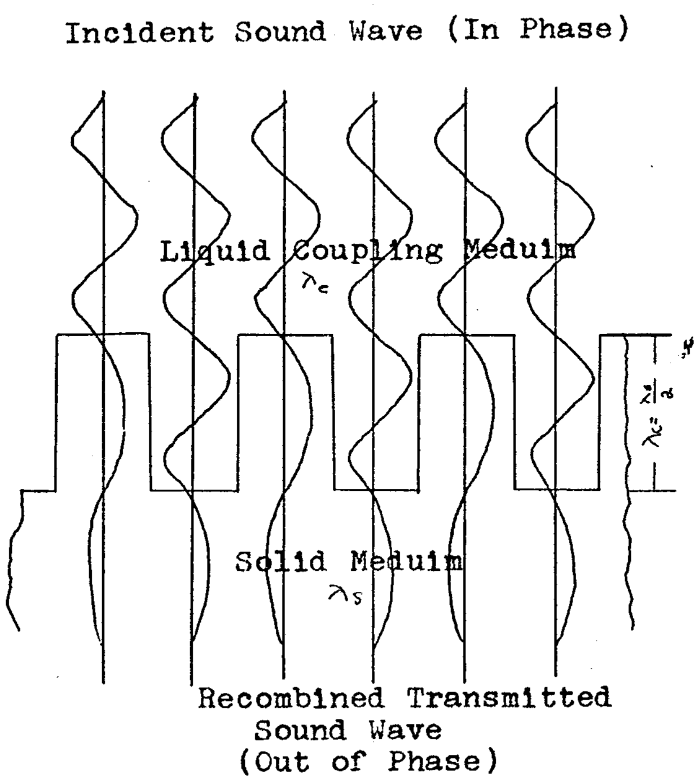


Fig. 15 Schematic of destructive interference caused by half-wave length surface roughness.

limestone, mortar, and concrete than are high frequencies.

ATTENUATION FROM COUPLANT THICKNESS INTERFERENCE

When the thickness of the couplant layer becomes less than the length of the wave train propagating through it, interferences occur. These interferences greatly decrease the sonic energy which enters the material being tested. The general expression for the energy-transmission coefficient for a plane sound wave, incident normal to a pair of parallel interfaces is given as (Kinsler and Frey, 1962, p. 138):

$$T = \frac{4Z_1Z_3}{(Z_1+Z_2)^2 \cos^2 k_2t + (Z_2+Z_1Z_3/Z_2)^2 \sin^2 k_2t} \tag{8}$$

where:

T = overall energy transmission coefficient

$Z_1 = p_1v_1$ = acoustic impedance in medium 1 (lbs/in^2-sec).

$Z_2 = p_2v_2$ = acoustic impedance in medium 2 (lbs/in^2-sec).

$Z_3 = p_3v_3$ = acoustic impedance in medium 3 (lbs/in^2-sec).

$k_2 = 2\pi/\lambda_2$ = propagation constant of intermediate layer (inches).

t = thickness of the intermediate layer (inches).

The energy-transmission coefficient T may be plotted as a function of thickness (Fig. 16). In addition, the special cases of:

(1) A very thin central layer

(2) A half-wave length central layer

(3) A quarter-wave length central layer

may be investigated by examining the form of Eq. (8) under these special conditions.

Case I: A very thin central layer ($k_2 t \ll 1$). For this case, the cosine term in Eq. (8) tends to unity and the sine term becomes negligible. Under this condition, the expression T reduces to the single interface transmission coefficient, given by:

$$T = 4Z_1Z_3/(Z_1 + Z_3)^2 \tag{9}$$

which is identical to Eq. (4).

Case II: A half-wavelength central layer ($k_2t = n\pi$). For this case, the energy transmission coefficient assumes the same form as for a thin layer, i.e., Eq. (9) applies.

Case III: A quarter-wavelength layer $k_2t = (2n - 1)\pi/2$. Under this condition, Eq. (8) reduces to the form:

$$T = 4Z_1Z_3/(Z_2 + Z_1Z_3/Z_2)^2 \tag{10}$$

From Eq. (10), it is evident that if $Z_2^2 = Z_1Z_3$, i.e., if Z_2 is made to equal the geometric-mean of the two outer media, then T will equal unity.

Thus, if a couplant (such as glycerine) has two high

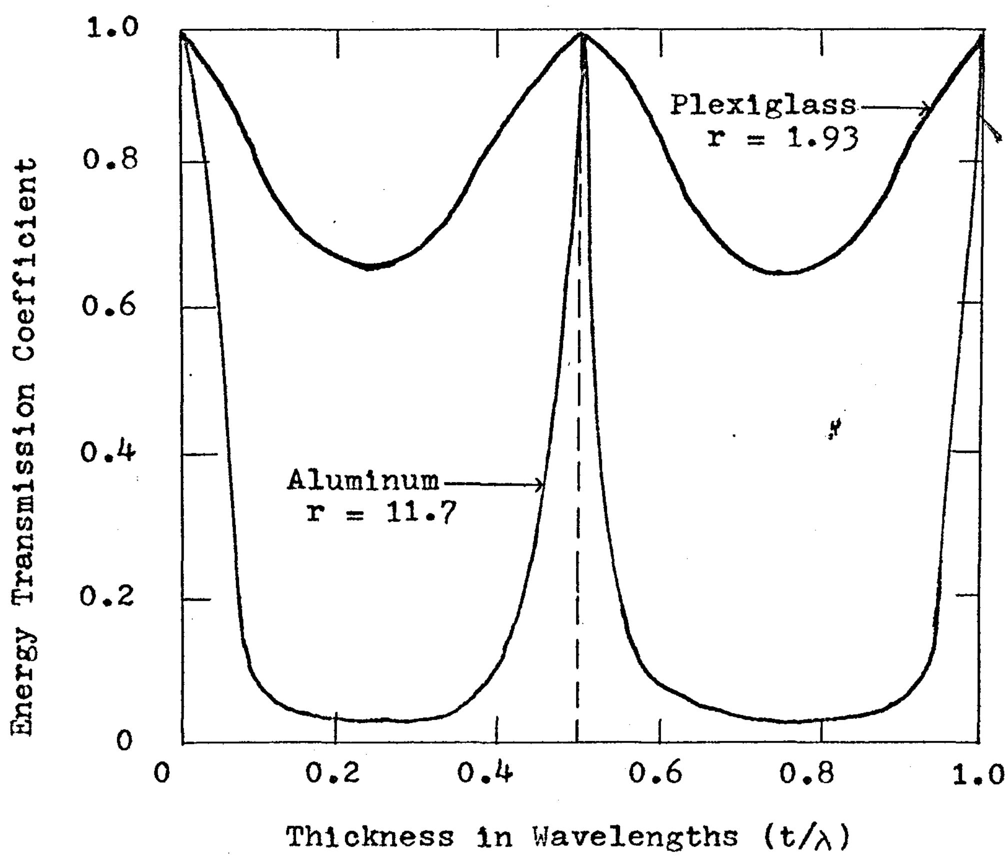


Fig. 16 Transmission coefficient as a function of thickness.

acoustic impedance media on either side, as is the case for plastic structures applied to limestone, mortar, or concrete, and provided the couplant layer is much less than a wavelength in thickness, then maximum permitted transmission will be obtained. This also minimizes surface roughness interference.

SECTION III

RESULTS OF LABORATORY RESEARCH

This section describes the work which was performed in the laboratory in an attempt to optimize the performance of the thickness gage. Each research topic is described separately below.

BONDING OF CRYSTALS TO BASE-PLATE

The acoustic transmitter as first developed used a silicon jelly to couple the piezoelectric crystals to the base-plate. This enabled changes to be made to the unit in the development stage without damaging the crystals. However, due to the low signal output voltage, it was decided to bond the crystals to the base-plate with water soluble glue. The advantages from the use of this hard bond between crystals and base-plate were found to be:

(1) Higher power output (increased by a factor of 2).

(2) Higher signal-to-noise ratio (increased from 2 to 3.4).

(3) Signal easier to locate.

(4) Less maintenance.

OPTIMUM SEPARATION OF JAMES TRANSDUCERS

Initial tests indicated that the velocity measurement procedure was rather inaccurate with a lack of repeatability in the measurements. Tests were therefore performed in the laboratory with the James transducers placed at various distances apart on a set of concrete blocks. The acoustic velocity was measured as a function of transducer separation distance. The results of these tests are shown in Figure 17. The vertical bars show the range over which the velocities were spread for each separation distance. From this plot, it can be seen that the repeatability of the velocity measurement improves with increasing transducer separation. However, due to increasing signal attenuation with separation distance, the optimum separation of the transducers was found to be on the order of 18 inches.

ORIENTATION OF JAMES TRANSDUCERS

Even with the optimum transducer separation distance established, errors of $\pm$ 2 per cent were still encountered in the velocity measurements. Further laboratory tests showed that the velocity measurement varied with the relative orientation of the transducers. It was learned that, although the transducer housing is circular with a 4-inch diameter, the piezoelectric crystal is rectangular. The actual separation distance of the crystals therefore varies with the orientation of the transducers. Figure 18 shows two possible positions of the James transducers,

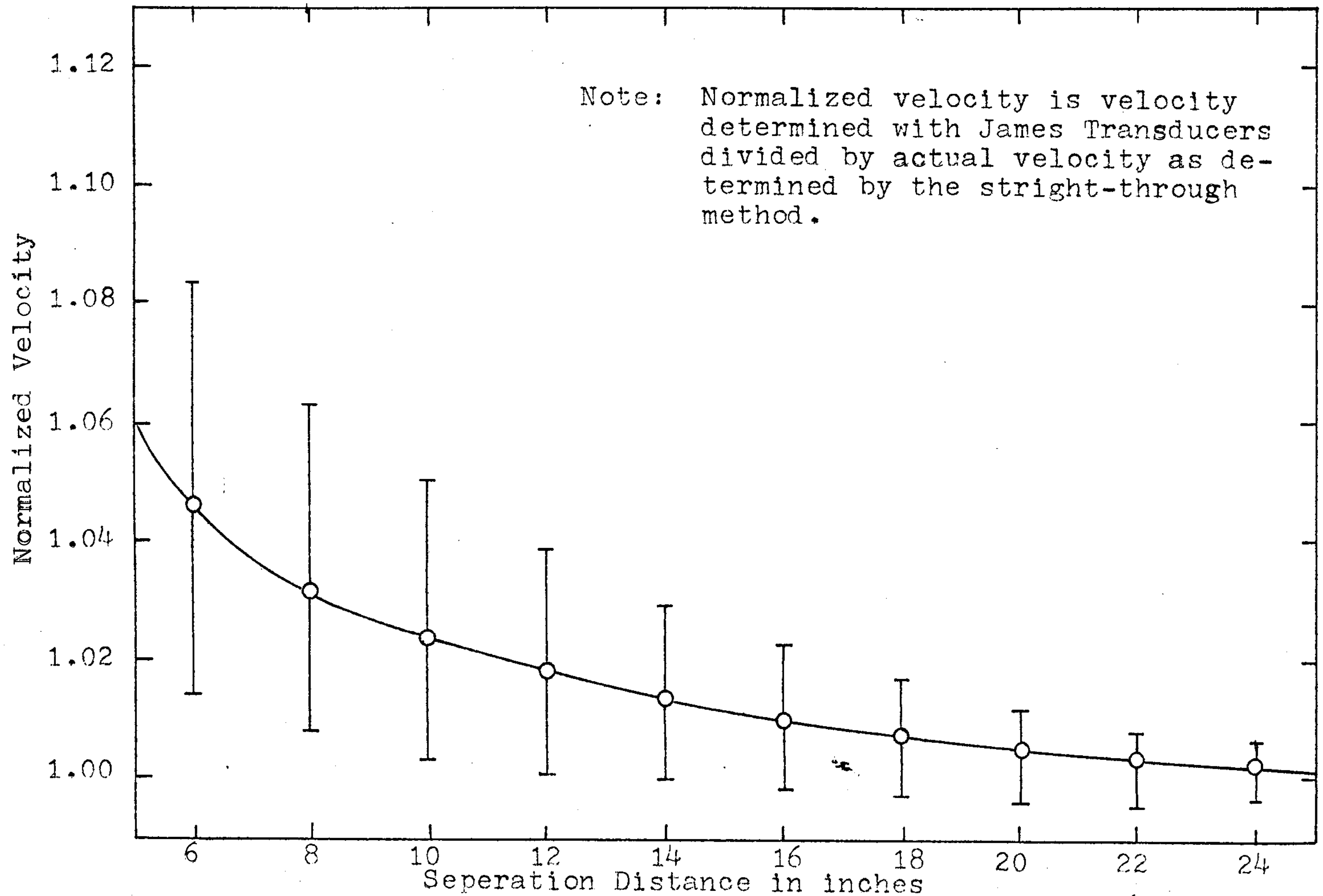


Fig. 17 Velocity response of the James Transducers as a function of separation distance.

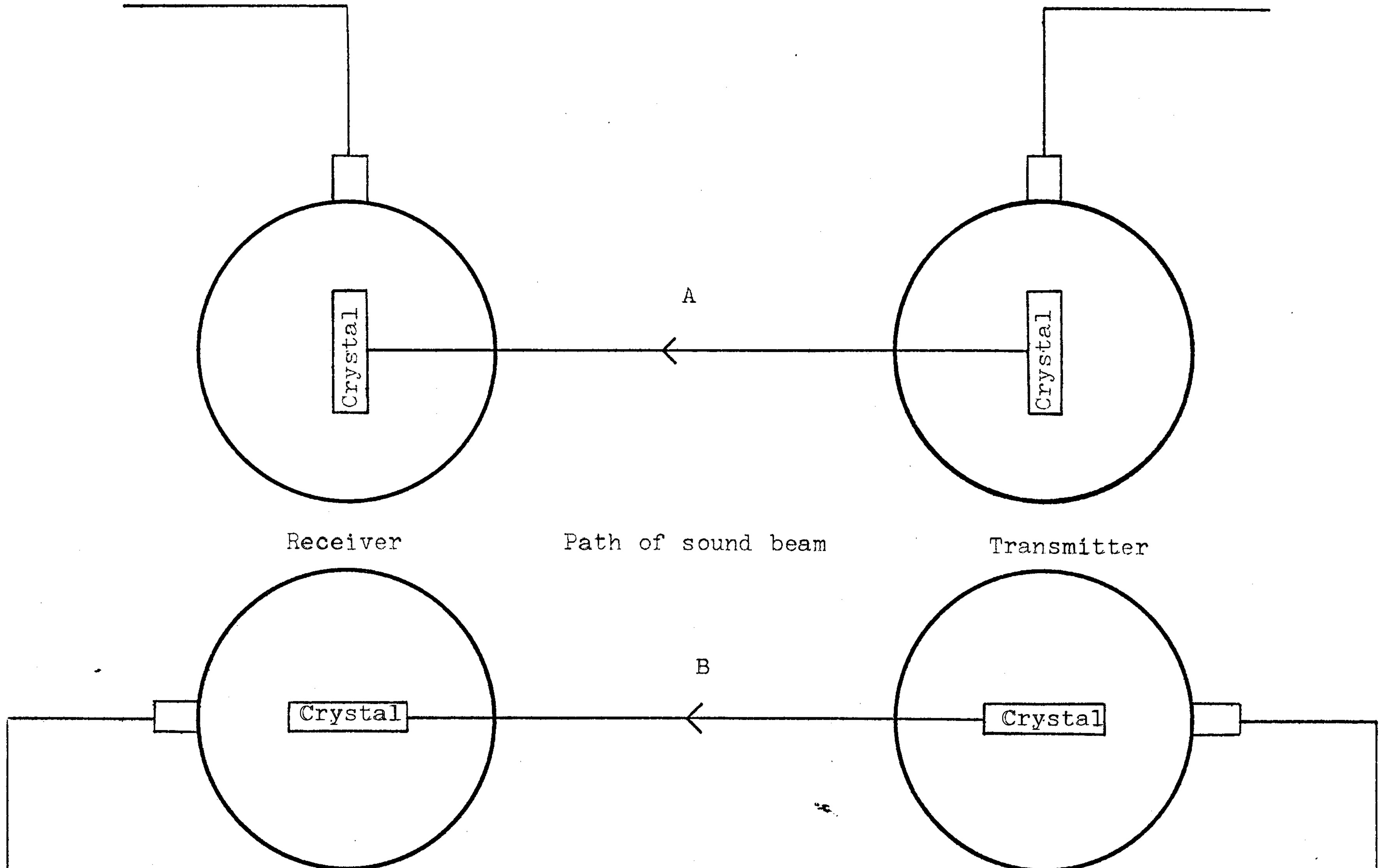


Fig. 18 The James Electronics Transducers in positions of minimum and maximum deviations from a point source.

position B having rotated 90° from position A. The tests showed that random orientation of the transducers could result in a maximum error of 1 per cent in the velocity measurements.

ADDITION OF WEIGHTS TO THE JAMES TRANSDUCERS

It was noted that the acoustic delay time through the James transducers, when placed face to face, varied from 30 μsec to 35 μsec. At first it was thought that this was due to temperature variations at the time the measurements were taken.

Delay time measurements were taken in the laboratory over a temperature range from 0°C to 30°C (Fig. 19). The rate of change of delay time was found to be 0.08 μsec/min. Since the maximum time required to take velocity measurements on any test site is less than 5 minutes, temperature variations could not be responsible for the comparatively large variations in delay time.

Further tests showed that the pressure with which the transducers were held together during the delay time measurement was a critical parameter. Variations in this pressure were shown to alter the delay time by several seconds. In order to get consistent delay times, a weight

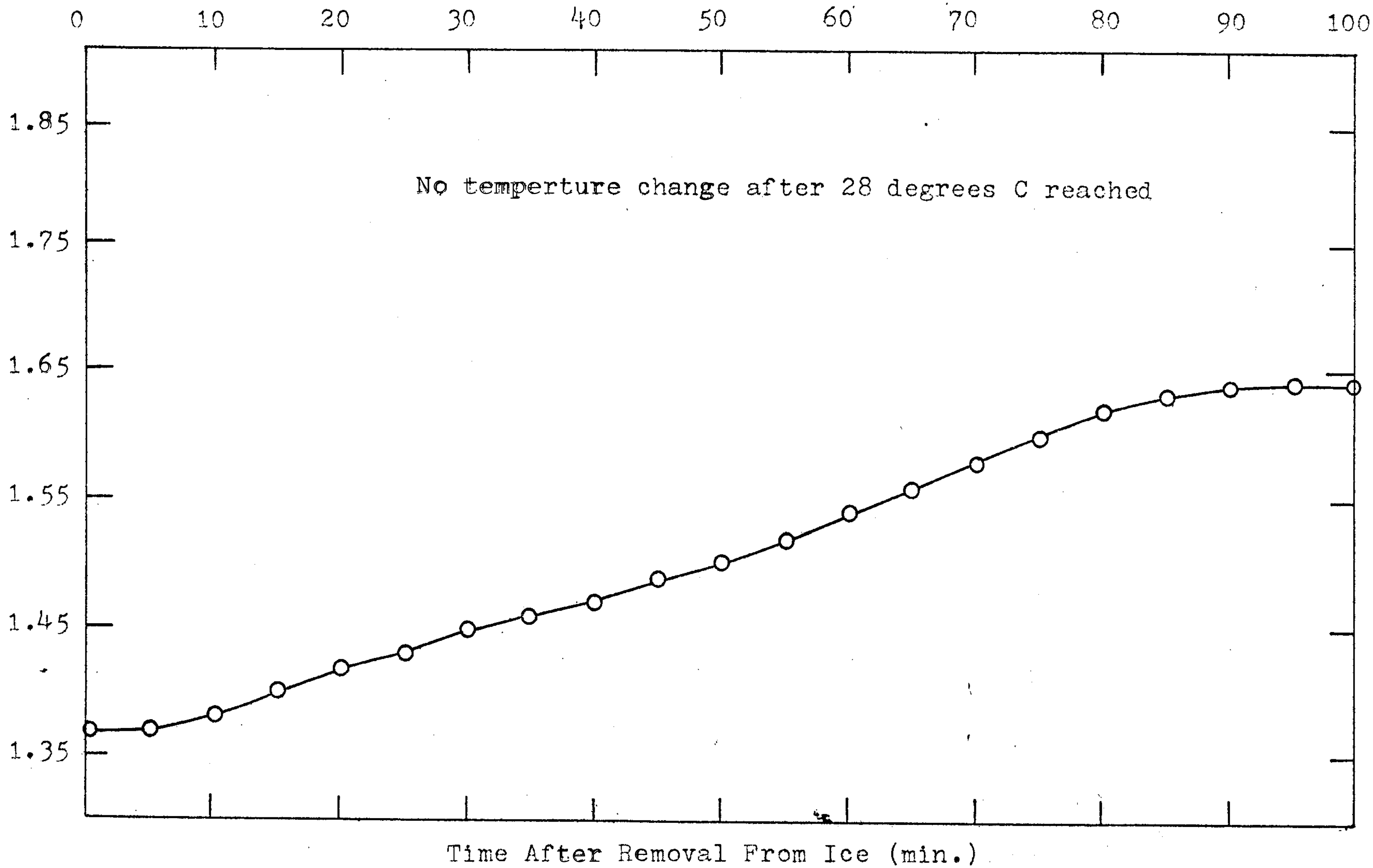


Fig. 19 Change in transducer delay time as a function of time from 0 degree C to 28 degrees C.

of 12.6 lbs. was permanently attached to each transducer. Using this constant pressure it was found that the delay time would not vary by more than 0.5 secs under normal conditions.

During the initial tests the James transducers had been pressed together by hand to get the delay time. The transducers had also been pressed against the test site by hand to get the transit time measurement for velocity. The use of the constant pressure method, together with the other improvements described above, has resulted in velocity measurements in the laboratory which are repeatable to within ± 1 per cent.

EFFECT OF SURFACE ROUGHNESS ON VELOCITY MEASUREMENT

Tests were conducted on specially prepared concrete blocks to examine the effects of surface roughness on the measurement of acoustic velocity. The results are tabulated below.

Table 1

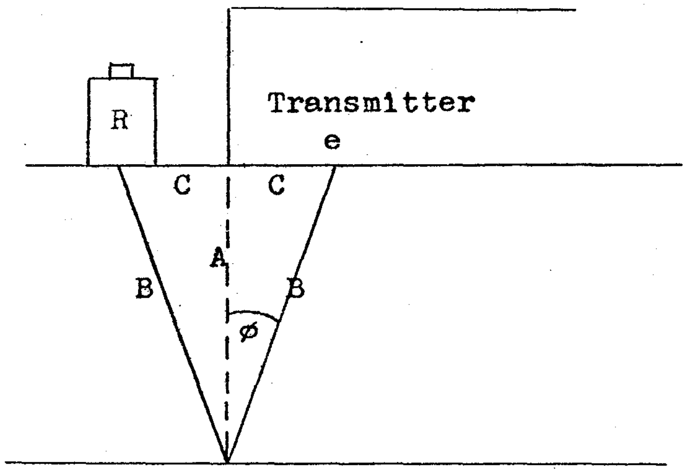
Surface Roughness (Groove Depth)	Change in Velocity
0.0" -- 0.375"	less than 1%
0.375 -- 0.517"	2.5% decrease (maximum)
0.517 -- 0.704"	2.7% decrease (maximum)

Thus, if the maximum relief encountered on the test surface is less than 0.375 inches, surface roughness should have no appreciable effect on acoustic velocity measurement.

DETERMINATION OF THE DISTANCE FACTOR

The transit time used in the thickness calculation refers to the time taken by the acoustic pulse to travel through the test site and back in a path that is perpendicular to the plane of the bottom surface of the transmitter. However, the pulse which is picked up by the receiver placed in the center of the transmitter has deviated from this perpendicular path. The distance traveled by the acoustic pulse through the concrete is, therefore, more than twice the actual test site thickness. The ratio of the total distance traveled by the acoustic pulse to the test site thickness is called the "distance factor". The measured transit time of the acoustic pluse through the test site has to be divided by this factor in order to get the transit time for use in the thickness calculation.

The method which was used to calculate this factor is shown in Figure 20. The thickness A was found with a mechanical thickness gage. The distance 2C represents the lateral separation of the receiver and the "exit point"



A = Test Site Thickness

2C = Distance from Exit Point (e) to Reception by Receiver (R).

$$\tan \phi = \frac{C}{A} \qquad \phi = \tan^{-1} \frac{C}{A}$$

$$\frac{A}{B} = \cos \phi \qquad \frac{B}{A} = \frac{1}{\cos \phi} = \frac{1}{\cos\left(\tan^{-1} \frac{C}{A}\right)}$$

Fig. 20 Calculation of the distance factor.

of the acoustic signal from the transmitter. Since the "exit point" is a function of the thickness of the test site, the distance factor was found to vary between 2.03 and 2.05 for test sites ranging in thickness from 6 to 12 inches. In general, prior knowledge of the approximate test site thickness cannot be assumed. This problem can be overcome by:

(1) plotting a curve of "distance factor" vs. thickness,

(2) plotting a curve, for a family of velocities, of transit time vs. thickness, and

(3) deriving from the equations of these graphs a nomograph on which it will be possible to cross plot velocity and transit time to obtain the true thickness (French and Vierck, 1963, pp. 639-657).

For the limited range of thicknesses measured in the laboratory, a constant factor of 2.04 was used.

SECTION IV

LABORATORY THICKNESS MEASUREMENTS

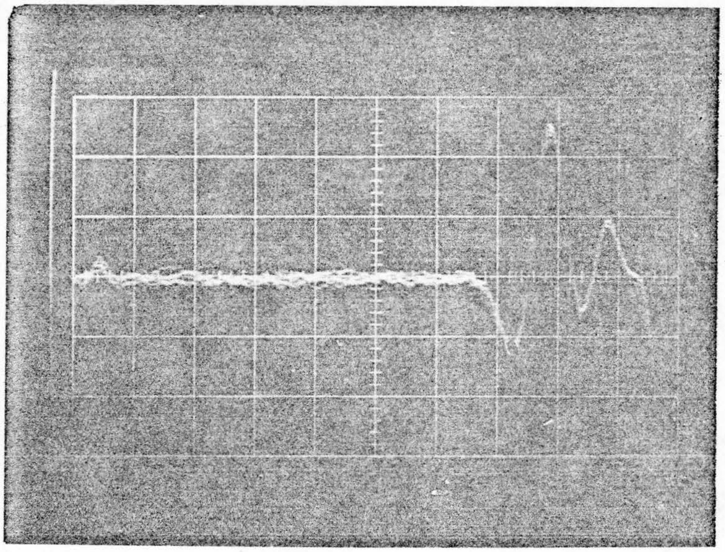
Normally, when the thickness of an area needs to be measured and only the top surface is accessible, a core is cut out of the area and the thickness of this core is taken as the thickness of the area in question. This method, while being accurate for the limited area of the core, leaves a hole in the test site. For some purposes, this destruction of the immediate test site is acceptable. In other cases it is not. Thickness measurements made with ultrasonic signals do not damage the test site in any way.

MATERIALS MEASURED

Under laboratory conditions, three blocks of Indiana limestone, five mortar blocks, and five concrete blocks were measured. After these blocks had been measured with the ultrasonic gage, they were measured with a mechanical gage. The results are presented in Table 2. Figure 21 shows a typical velocity signal and the manner in which velocity is calculated. A representative signal used in calculating the thickness of the test site is shown in Figure 22.

Table 2

Material	Velocity (in./sec.)	Thickness Measured Ultrasonicly (in.)	Correct Thickness (in.)	Per Cent Error
Limestone	171,900	6.11	6.06	+0.83
Limestone	173,200	11.71	11.75	-0.34
Limestone	172,100	11.92	11.90	+0.17
Mortar	154,800	4.09	4.04	+1.24
Mortar	155,100	7.68	7.59	+1.18
Mortar	154,900	9.09	9.03	+0.67
Mortar	155,500	9.41	9.47	-0.64
Mortar	155,700	10.07	10.03	+0.39
Concrete	167,600	6.49	6.40	+1.41
Concrete	163,500	7.18	7.09	+1.27
Concrete	160,100	8.33	8.26	+0.80
Concrete	158,000	9.11	9.13	-0.22
Concrete	158,800	10.07	10.12	-0.40



Typical Velocity Signal

Velocity Calculation

Delay Time (from oscilloscope) = 33.4 μsec.

Total Transit Time (from oscilloscope) = 146.6 μsec.

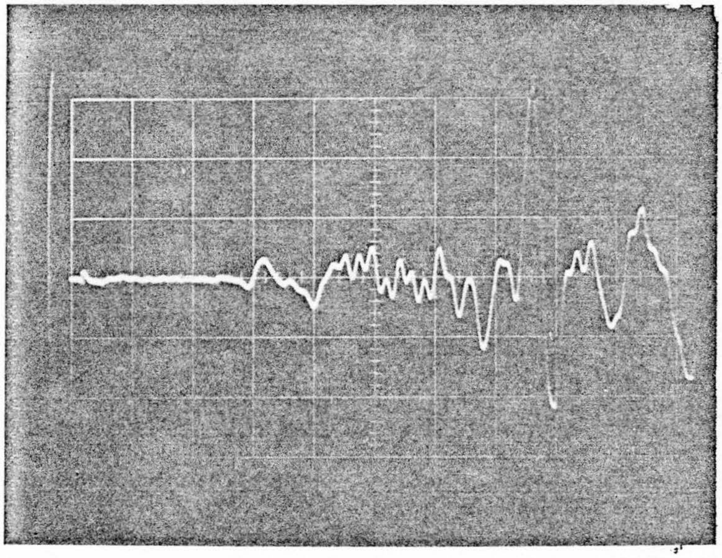
Actual Transit Time = 146.6-33.4 = 113.2 μsec.

Separation Distance = 18 in.

$$\text{Velocity} = \frac{\text{Separation Distance}}{\text{Time}}$$

$$\text{Velocity} = \frac{18 \text{ in.}}{113.2 \text{ sec.}} = 158,800 \text{ in./sec.}$$

Fig. 21 Velocity signal display and calculation of ultrasonic velocity.



Reflected Ultrasonic Signal

Thickness Calculation

Delay Time (from oscilloscope) = 32.4 μsec.

Total Transit Time (from oscilloscope) = 161.9 μsec.

Actual Transit Time = 161.9-32.4 = 129.3 μsec.

Velocity (from Fig. 21) = 158,800 in./sec.

$$\text{Thickness} = \frac{\text{Velocity X Time}}{\text{Distance Factor}}$$

$$\text{Thickness} = \frac{158{,}800 \text{ in./sec. X } 129.3\ \mu\text{sec.}}{2.04}$$

Thickness = 10.07 in.

Fig. 22 Display of an ultrasonic signal reflected through concrete and calculation of the thickness of the concrete.

CONCLUSIONS

As can be seen from Table 2, the accuracy of the thickness measurements is better than ± 2 per cent in all cases. In the case of eight inches or more, the accuracy is better than ± 1 per cent. The larger error encountered for thicknesses less than eight inches can be partially attributed to the "distance factor". A distance factor of 2.04 was used in all the measurements. This factor is correct for 10 inches, but, since this factor varies inversely with thickness, it is too small for the lesser thicknesses. Also, the inherent inaccuracy of the time delay mechanism is more pronounced for lesser thicknesses. The average error, disregarding thicknesses less than 8 inches, for the limestone is 0.26 per cent; for the mortar 0.57 per cent; and for the concrete 0.47 per cent. As mentioned before, the greater accuracy of the limestone measurements is probably due to the physical characteristics of the material, which results in a relatively large reflected signal with a large signal-to-noise ratio.

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